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Protocol for foliage modeling and light partitioning in *Coffea arabica*

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Highlights: Virtual coffee trees were reconstructed using partial morphological data, newly developed modules, AmostraCafe3D and VirtualCafe3D, and VPlants software. Leaf area size, STAR and transmitted PAR in different horizontal layers were computed on the virtual coffee plants and confronted to measurements.

Keywords: 3D reconstructions, STAR, tree layer samples, VPlants

INTRODUCTION

The architecture of *Coffea arabica* L. is described by Roux's model and characterized by continuous growth and branch dimorphism. The main axis (first order axis) is orthotropic, composed of internodes of relatively regular length with opposite and decussate leaves. This orthotropic axis bears plagiotropic branches of 2nd to 5th orders that are responsible for berry production. The leaves of plagiotropic branches follow decussate phyllotaxy, but both internode torsion and petiole angle reorient leaves, resulting in dorsiventral shoots (Dengler 1999). The lowest order plagiotropic branches are of great longevity. The highest branching orders appear in three- to four-year-old coffee plants, so that the structure becomes complex in the early tree life. Each year foliage formation precedes the intensive investments in berry ripening. The foliage light interception and shading could induce important impacts on final coffee quality (Vaast et al. 2006).

Functional-structural plant models offer the way to study the crown and tree development on the basis of a structurally accurate description that combines resource capture at the same level of detail (Sievänen et al. 2010). The aims of this study were to (a) reconstruct a 3D structure of whole *C. arabica* trees using detailed or partial morphological information collected on whole plants and (b) use these virtual coffee trees to estimate leaf area distribution and light interception partitioning between horizontal layers.

TREE MEASUREMENTS, ABSTRACTION AND CODIFICATION

Coffee mock-ups were reconstructed using VPlants software (http://www-sop.inria.fr/virtualplants/wiki/doku.php?id=software#software) on the basis of tree coding using multiscale tree graph - MTG (Godin and Caraglio 1998) with three scales of description (plant, axe and metamer). The main axes were always described at metamer scale and numerous variables were collected: length of each internode; length/width/elevation angle/cardinal orientation of leaves, and position/orientation/total length of borne plagiotropic branches. When young plants were measured, the same variables plus the flower and berry number and positions were collected for 2nd order plagiotropic branches. On adult plants, four 2nd order plagiotropic branches were sampled (each oriented to one cardinal point), to represent each 40 cm-thick layer along the vertical tree profile. These sampled 2nd order plagiotropic branches were described at metamer scale plus the detailed description of their lateral plagiotropic branches of 3rd to 5th order. All other 2nd order plagiotropic branches were described by their position along the orthotropic axis, total branch length, berry number and the cardinal orientation.

For this study four three-years-old adult plants and five ten-month-old seedlings of cv. IAPAR 59 (popular cultivar in Paraná coffee-culture) were measured in the experimental field (IAPAR, Londrina, Brazil - 23° 18' 37" S, 51° 09' 46" W, 585 m altitude). The adult ones were planted in a distance 0.5 m in line and 2.5 m between lines in 2009, and the seedlings in 2012. They were grown under non-limited water and nutrition conditions. The adult plants were considered at two periods, one relative to berry ripening (April 2012) and second to berry harvesting (July 2012).

AMOSTRACAFE3D – MODULE FOR INCLUSION OF MISSED DATA TO PARTIALLY MEASURED BRANCHES

A module (called AmostraCafe3D), aiming at reconstructing the whole coffee plants based on branch sampling data, was developed in Python. The output MTG are the input MTG containing the collected data augmented with calculated information for plant reconstruction. The first step considers the reconstruction of 2^{nd} order partially measured branches, based on point wise average lengths of the internodes obtained from the completely described branches situated on the same layer and approximately similar cardinal orientation (actually the orientation is not always clear, due to internode torsion) of four plants. The following steps treat the leaf and fruit number, and 3^{rd} to 5^{th} order plagiotropic branch reconstructions based on estimated probability of leaf, branching and berry occurrences. The estimated probabilities were calculated from occurrences built for measured 2^{nd} order plagiotropic shoots, considering the metamer index and layer/orientation/ period of sampling. 'Random' Python library was applied to randomly display leaves, berries and lateral branches along the 2^{nd} order shoots that were partially measured, based on previously estimated probabilities. The adapted leaf area index calculated from these reconstructed plants (Fig. 1B) is considered for the validation of foliage size produced by AmostraCafe3D.

VIRTUALCAFE3D – MODULE FOR GEOMETRICAL ADJUSTMENTS

The coffee plant reconstructions were constrained by attributed phyllotaxis of 90° and 180° inducing errors in leaf and branch positions and orientations. Also, the leaf attributes were not assigned to a specific leaf within each pair in the MTG. Thus, a module named VirtualCafe3D was developed under the NetBeans IDE platform (Java Standard Edition), to overcome these shortcomings. The algorithm consists of: 1) spatial settings of leaves originated on plagiotropics (from 2^{nd} to 5^{th} branching order), 2) spatial settings of leaves originated on orthotropic axis and 3) correction of the branch orientation. The general solution for leaf and branch orientation corrections consists of the replacement of a node with two leaves by two successive nodes, each with one leaf, separated by a very short "virtual" internode (Matsunaga and Rakocevic, 2011). The algorithmic steps vary for each solved adjustment. The validation was performed by reconstructing the 3D mock-ups using PlantFrame function and by visually checking the branch and leaf orientation in PlantGLViewer in the VPlants software (Pradal et al. 2008).

LEAF AREA ADJUSTMENTS AND LIGHT INTERCEPTION COMPUTATION

Virtual trees were then constructed using PlantFrame function of VPlants and visualized using PlantGLViewer. A coffee leaf was constructed using 16 triangles in GEOM module and transposed into the Cartesian coordinate system by the adjustments for 1 cm length-L x 1 cm width-W in VegeSTAR software (Adam et al. 2006). To set the allometry, the adapted coefficients for LW leaf shape model (Antunes et al. 2008) were introduced. Two measurement methods were performed to assess the foliage reconstructions, one direct and one indirect (Fig. 1).

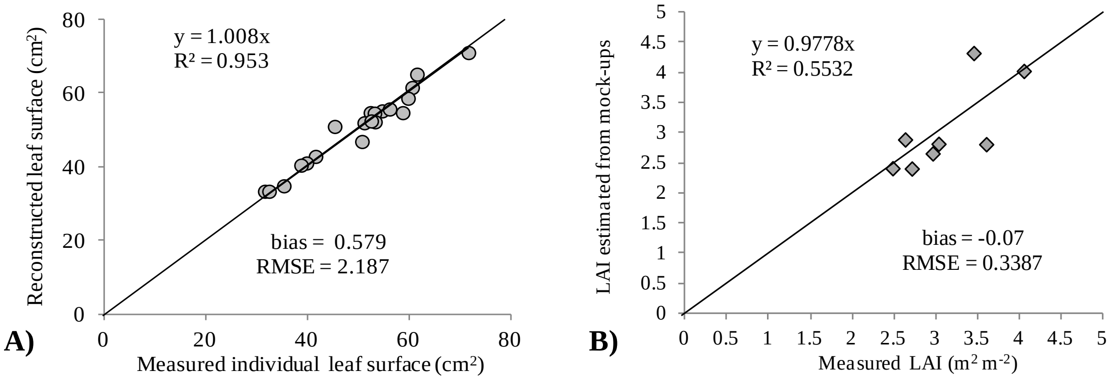

Fig. 1. Adjustments of measured leaf areas to reconstructed ones - R^2, bias, RMSE, and 1:1 line are indicated. **A**) Individual leaf surfaces measured with LICOR 3000 and **B**) Adapted leaf area index (LAI) for coffee plants measured with LICOR 2000.

The direct method considered the individual leaf surface measurements. Ten leaves were measured (LICOR 3000) at each period of observation and their surface was compared to outputs of individual leaf reconstructions from VegeSTAR (Fig. 1A). The indirect method considered the leaf area index (LAI) measurements with LICOR 2000 (Fig. 1B). It was adapted for coffee plants by a set of ten measurements: the first and the last one shot above the canopy, while eight measurements correspond to 5 cm and 35 cm distance of the trunk points below the plant crown and oriented to four cardinal points. LAI outputs correspond to the crown projected on soil (calculated from x- and y-axis projections). LAI of eight mock-ups fitted well to measured plants (bias = -0.07 and RMSE=0.338 at Fig. 1B). The measurements with LICOR 2000 were accepted when over- or underestimation was about 10% for coffee plants (Angelocci et al. 2008).

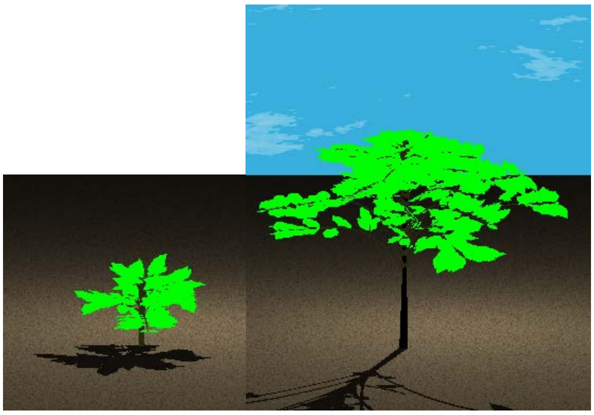

Fig. 2. Visualisations of juvenile and adult coffee plant mock-ups.

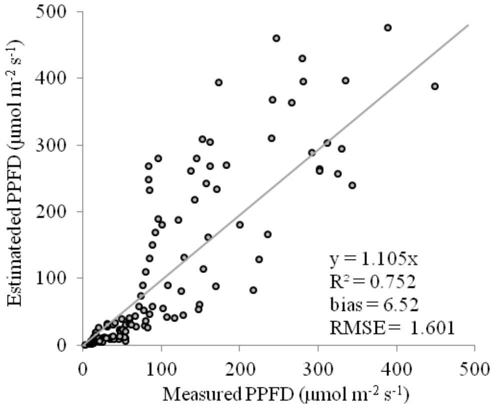

Fig. 3. Measured *versus* estimated transmitted radiation calculated in VegeSTAR from mock-ups.

The visualisation of mock-ups built for one seedling (from detailed description at metamer scale), and one adult plant (from sampling) is shown on Fig. 2. Silhouett**e** to Total Area Rati**o** (STAR) was computed with VegeSTAR. Directional light interception for 16 directions and STAR sky-integrated indexes of light interception were estimated under Standard Over Cast (SOC) sky radiance distribution. Those STAR values were calculated within 40 cm-thick layers on coffee crown. The transmitted PAR was calculated for the representative plants based on the estimated interception. STAR outputs were calculated for each 15 minutes, over two particular days (14 April and 19 August, 2012) during which morphogenetic and light measurements were performed (Fig. 3). The relative high bias observed between estimated and measured values could result from estimation performed on isolated plants whereas measurements performed in field were affected by distances between plants in the stand. This protocol will be further improved and applied to estimate the light interception efficiency of foliage positioned in diverse layers along vertical coffee tree profiles, cardinal point orientation and stages of development, aiming at better understanding the local shading impacts on final coffee quality.

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